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ATTACHMENT 3

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GAS FLOW AND FLUIDIZATION IN A THICK DYNAMIC REGOLITH: A NEW MECHANISM FOR THE FORMATION OF CHONDRITIC METEORITES. Shaoxiong Huang and Derek W. G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas, 72701, USA

We have previously shown that size and density sorting in a regolith which has been "fluidized" by the passage of gases from the interior of the body can quantitatively explain metal-sillicate fractionation, an important property of ordinary chondrites. Here we discuss whether the flow rates and flux of volatiles expected from a primitive parent body are likely to be sufficient for this mechanism. Many meteorite parent bodies may have contained volatiles. From a consideration of heat diffusion and fluid mechanics, we calculate the gas flow rate of volatiles (e. g., water) in the regolith of an asteroid-sized object heated by ^{26}Al. Our calculations show that the flow velocities and flux of water vapor are sufficient to produce conditions suitable for fluidization. Other heat sources have yet to be considered, but literature work suggests that they may be equally effective.

The metal-silicate fractionation experienced by chondritic meteorites has long been recognized as an important process in evolution of the early solar system. Since Urey originally argued that the separation of metal and silicate could not have occurred in a planetary setting (thinking that the only feasible process involved melting) [1], a variety of nebular processes have been proposed, involving magnetism [2], crystal growth [3], ductility of the metal [4] and inhomogeneous accretion [5]. None of these mechanisms has been quantitatively modeled and thus are hard to evaluate. Chondrules and metal have also experienced soze-sorting so that each class has a characteristic texture. Sorting by aerodynamic drag in the nebula [6] is a promising means for accounting for the size distribution of metal and chondrules in particular chondrite classes, but cannot explain the inter-class trends in chondrule to metal size ratio. This is not true of aerodynamic sorting in a regolith on a small asteroid-like parent body where the upward drag forces are balanced by downward gravitational forces to create what chemical engineers term a "fluidized bed". Using semi-empirical results from the literature, we find that metal-silicate separation in a thick regolith quantitatively produces the expected size and abundance distribution of metal and chondrules in the H, L and LL classes. Metal-silicate fractionation could have therefore occurred on meteorite parent bodies without the need for melting [7]. The gas flow rates required for are very low, ~1 and 10 mm/s for 10 and 100 km-radius parent bodies, respectively. Crucial to these ideas is whether the required flow rates and flux of volatiles on small asteroids are reasonable. This point is discussed here.

There are several lines of evidence that suggest that degassing of water and other volatiles would have formed a temporary atmosphere on an accreting asteroid [8]. Not only are many primitive objects in the solar system (e. g., carbonaceous chondrites and comets) still rich in volatiles, especially water, but there is evidence for ample heat sources in the early solar system that would be capable of evaporating these volatiles, such as internal heat sources like ^{26}Al [9, 10] and external heating sources like impacts [11]. We here discuss internal heating by ^{26}Al and calculate temperature profiles using the method of Miyamoto *et al.* [12]. An initial uniform temperature for the parent body of T_o (= 273 K) is assumed, and the heat generated radiating at the surface into a medium at temperature T_o. Then the temperature as a function of time and depth is given by:

$$T = T_o + \frac{2hR^2Q}{rK} \sum_{n=1}^{\infty} \frac{1}{1 - \lambda/\kappa\alpha_n^2} \cdot \frac{[\exp(-\lambda t)-\exp(-\kappa\alpha_n^2 t)]\sin(r\alpha_n)}{\alpha_n^2[R^2\alpha_n^2 + R.h(R.h-1)]\sin(R\alpha_n)} \qquad (1)$$

where α_n, n = 1, 2,..., are the roots of $R\alpha \cot(R\alpha) + R \cdot h - 1 = 0$. R and r are the radius and radial distance from the center of the parent body, respectively. Other parameters are given in Table 1. The radii of the parent bodies are assumed to be a few tens of km, consistent with constraints from thermal conductivity of meteorites [13] and metallographic cooling rates [15]. For ^{26}Al/^{27}Al of 1 - 6 x 10^{-6}, the calculated maximum temperatures near surface (at r = 82.5 km) range from 330 to 630 K for an object of 85 km-radius.

In the present study, we assume the parent body was covered with a thick layer of regolith. Under internal heating, water vapor generated from the interior flowed through the regolith due to the temperature gradient. High permeability of the porous regolith greatly enhances gas flow. We consider the one-dimensional flow of gases and steady-state conditions. The gas flow rate (m/s) is calculated by applying Darcy's law [16]:

$$V = \frac{K_p}{\eta(1 + m)\Delta s P_2^m} \cdot (P_2^{1+m} - P_1^{1+m}) \qquad (2)$$

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where P_1, P_2 are vapor pressure of water at surface and bottom of regolith, respectively, and Δs is the depth of regolith, typically a few kilometers or less [17]. The upper limit of regolith depth can also be estimated using the largest crater depth observed for asteroids, which suggests a magnitude of several kilometers and we use $\Delta s = 2.5$ km in our calculations. The main variable in this equation is permeability (K_p), probably 10^{-9}-10^{-11} m^2 [16,18]. Other parameters are also given in Table 1. The vapor pressure of water is calculated from the temperature, which is calculated from equation 1 at various ^{26}Al abundances. The results of $^{26}Al/^{27}Al$-flow rate-permeability variations are plotted in Fig. 1.

The calculated gas flow rates are on the order of minimum flow rates required to sustain fluidization of chondritic objects with reasonable ^{26}Al abundances and permeability values. The inferred initial $^{26}Al/^{27}Al$ ratio from CAI's (6×10^{-5}) [9] may not be representative of the entire asteroid. The only detected excess ^{26}Mg outside of the CAI's has an inferred initial $^{26}Al/^{27}Al$ of $8 \pm 2 \times 10^{-6}$ [10]. We thus adopt $^{26}Al/^{27}Al$ of 1 - 6 x 10^{-6} in our calculations. Although we chose R = 85 km in our calculations, using different values of objects yieldssimilar results. This model also applies to enstatite and carbonaceous chondrites except that for carbonaceous chondrites the source of gas flow is probably ice and thus the ice-water phase transition must also be considered.

One interesting aspect of these calculations is that we can quantitatively address the duration of degassing, although metal-silicate separation in a fluidized bed occurs very rapidly (generally less than a few minutes in most laboratory experiments [19]). We assume that vapor transport in a heated porous body is in a state of quasi-static equilibrium. Under this assumption, the degassing zone is likely in a state of vapor-condensate equilibrium: the vapor pressure is maintained as long as condensate is available. We calculate the duration of degassing using the equation $t = W/(U\,S)$, where W is the mass of water present in the asteroid, U the rate of mass flow per unit cross section and S the surface area of the asteroid. The calculated time scale of degassing is 1 - 100 years, depending on the permeability of regolith (10^{-9}-10^{-11} m^2 in our calculations), for an object of 85 radius-km with 10 % v/v of water and $^{26}Al/^{27}Al$ of 5×10^{-6}.

Shock degassing of volatiles seems to be a promising mechanism for degassing during accretion of planetesimals [11, 20]. Using the gas thermal escape model developed by Hunten [21], we calculated the degassing rate of water vapor at surface (at T = 500 K) for objects of 10 -100 km-radius (Fig. 1). These gas flow rates are sufficient to sustain fluidization of chondritic materials, although the flow rates are very dependent on the size of parent body.

It seems clear to us that for ^{26}Al, as well as impact, heated meteorite parent bodies the predicted flow velocities and flux of volatiles are ample to produce conditions suitable for fluidization which we have previously shown to provide a mechanism for metal-silicate fractionation and size-sorting observed among ordinary chondrites.

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Table 1. Parameters used for the calculations

Thermal conductivity[13]	$K = 1.0\ W\ m^{-1}\ K^{-1}$
Thermal diffusivitry [13]	$\kappa = 5.0 \times 10^{-7}\ m^2\ s^{-1}$
Heat generation [14]	$Q = 11.67\ (^{26}Al/^{27}Al)\ W\ m^{-3}$
Decay constant (^{26}Al)	$\lambda = 9.63 \times 10^{-7}\ y^{-1}$
Emissivity [13]	$E = 0.8\ (h = 1.0\ m^{-1})$
Adiabatic flow	$m = C_v/C_p = 0.857$ s
Viscosity (water vapor)	$\eta = 1.1 - 2.2 \times 10^{-5}$ Pa s

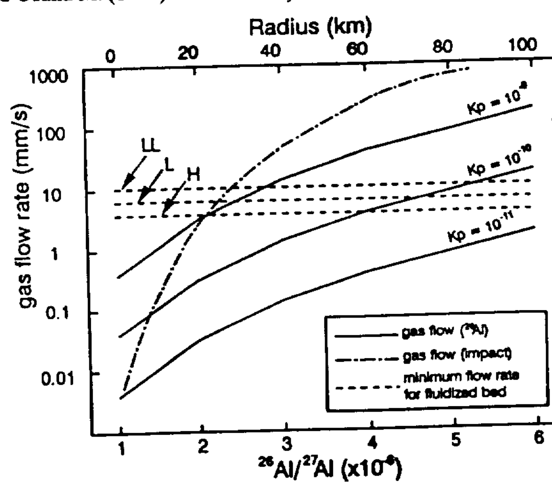

Fig. 1 Calculated gas flow rate in regolith on a meteorite parent body as a function of (1) ^{26}Al abundance (bottom axis) and permeability (K_p, m^2) of the parent body and (2) radius of the parent body (top axis) for an impact heated object. The flow rates required to sustain fluidization of H, L and LL chondrites [7] are also indicated.